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PRINCIPAL INVESTIGATOR: James H. Stuhmiller, Ph.D.
Weixin Shen, Ph.D.

CONTRACTING ORGANIZATION: Jaycor, Incorporated
San Diego, California 92121-1002

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James H. Stuhmiller, Ph.D.
Weixin Shen, Ph.D.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Jaycor, Incorporated
San Diego, California 92121-1002

E-Mail:

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Trauma Assessment for Warrior's Medic

Technical Report

Prepared by:

Weixin Shen, Ph.D.
James H. Stuhmiller, Ph.D.

JAYCOR, Inc.
3394 Carmel Mountain Road
San Diego, California 92121-1002

Prepared for:

Commander
US Army Medical Research and Materiel Command
ATTN: MCMR-RMC
Fort Detrick, Maryland 21702-5012

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1.0 Introduction

1.1 Background

The US Army Medical Research and Materiel Command (MRMC), through its Telemedicine and Advanced Technology Research Center (TATRC) has programs to give the battlefield medic the technology to save lives, especially in the early, critical minutes after wounding or injury. It is not known at this time what will be needed to accomplish this mission. It probably involves sensors on the soldier to determine his physical and physiological state, location gear to know where he is, and communication gear to get the information to the commander so he can take action. The soldier's pack is already so heavy, however, that it is unlikely that more gadgets will be added simply to help the medical function. Therefore, for the foreseeable future, the medics will have to "piggy-back" on some other system.

A separate Army program is working on equipping the 21st century soldier with state-of-the-art sensors, computers, and communication gear to maximize his fighting ability. The Land Warrior (LW) Program is developing that equipment and will begin testing in the next year or so. The LW backpack contains a computer with a Dead Reckoning Module (DRM). The DRM is a plug in board containing a three-axis accelerometer, three-axis magnetometer, and pressure and temperature sensors. It works as an elaborate pedometer to calculate the soldier's motion on foot and serves as a back up to the GPS system.

MRMC wants to determine if the DRM could provide acceleration data that might indicate whether the soldier has been wounded. If so, it may be feasible to modify the on-board software to process the signal in this way and send a "911" call. If the current DRM is not adequate, then MRMC wants to know what would be the right data to collect so that technology could be inserted in future LW upgrades.

The next sections give more information on previous work and issues. In short, the nature of traumatic events and the performance of current technology, like the DRM, are not known. This project is to make a preliminary assessment of both.

1.2 Needs and Opportunity

1.2.1 Warrior's Medic (Zajtchuk and Sullivan, 1995).

Over the past 150 years, the percentage of battlefield casualties who die after reaching a medical facility (die of wounds) has decreased from 16% in the Crimean War to under 4% in recent wars. This improvement no doubt reflects both the gradual development of an organized system of rapid and safe evacuation of the wounded from the battlefield and the achievements of modern surgery. On the other

hand, over that same period of time, the percentage of battlefield casualties that die before reaching medical facilities (killed in action) has remained nearly constant at 20%.

Most battlefield deaths occur rapidly despite the fact that the median time required for a combat medic in the Vietnam conflict to reach and begin treating a combat casualty was only 4 minutes after wounding. Over 60% of battle deaths occurred in less than 5 minutes and less than 10% occurred in longer than 1 hour. About 50% of the soldiers killed in action in Vietnam exsanguinated and it is estimated that 20% of these could have been saved with simple first aid.

Emergency communication gear will be significant because it is believed that 90% of the time the wounded soldier can call for help. The other 10% of the time, however, the soldier is unconscious, incapacitated, or dead. If the incapacitating event or its immediate consequences can be detected, classified, diagnosed, and communicated, then rapid action can be taken to provide the aid that might save a considerable number of soldiers.

1.2.2 Warfighter Personal Status Monitor (WPSM) (Hegge and Levine, 1997)

Personal Status Monitor (PSM) is the technology and methodology for assessing components of individual medical readiness using physiological monitoring instruments on the body of the warfighter. WPSM is the application of this concept to the Land Warrior (LW) system.

The LW program provides an opportunity to make ambulatory monitoring of soldier readiness and sustainability and integrated feature of the soldier ensemble. Assessing metabolic functions, cumulative sleep and sleep loss, and other physiological stressors will give commanders sufficient warning time to rapidly employ ameliorative or preventative actions to maintain medical readiness. The fundamental PSM will be worn continuously in order to establish and maintain individual soldier response templates.

1.2.3 Land Warrior.

Land Warrior (LW) will equip soldiers on the battlefield with sophisticated sensors for various tactical purposes, a computer for analysis, and a communication suite. These are the elements needed to meet the WM and WPSM requirements. As the LW is field-tested and deployed, it will undergo continual and periodic upgrading of these systems which will offer more capability and more chance to introduce the components that will accomplish the MRMC goals.

1.3 Previous Work

1.3.1 PSM Program.

Previous work (Redmond and Hegge, 1985) has established the technical feasibility of observing physiological characteristics (heartbeat, breathing rate) from chest acceleration and activity

characteristics from wrist acceleration. This data appears to be adequate to determine many important normal activity parameters. The interpretation of traumatic events would seem plausible from acceleration data, but the feasibility has not been demonstrated. The PSM program has also presented conceptual ideas for fusing other measurements (voice timing, temperature, etc.) to provide a more complete and reliable monitoring system (Hegge, 1996).

1.3.2 LW DRM.

The LW is planning to include a Dead Reckoning Module (DRM) that is capable of detecting locomotion, acting as a sophisticated pedometer. The module contains orientation-sensing instruments that could detect more complex motion. Although the DRM in its current configuration is unlikely to detect physiological motion, it might be able to capture the consequences of traumatic events. The DRM provides one point of technology insertion into the LW system for monitoring functions.

1.3.3 MRMC Biophysical Modeling Program.

Previous work in this program has shown that many aspects of body response and subsequent trauma can be simulated with mathematical modeling. The goal of the project over the next three to five years is to build a whole body model that can be the basis for simulation and evaluation of a wide range of situations. Research in this area can be accelerated and focussed by MRMC to provide the biomechanical basis needed to design and evaluate equipment needed to meet the WM and WSPM requirements.

1.4 Issues and Objectives

It is not known what characterizes traumatic and normal events or how to discriminate them. Without this knowledge, a monitoring system (sensor type, placement, and interpretation) cannot be rationally developed.

LW DRM, as currently configured, samples too slowly to directly capture traumatic motion and has insufficient CPU capability to handle any analysis needed by WM or WPSM.

The WM and WPSM function must coexist with, or more correctly, be subservient to the tactical mission of the LW. Consequently, the medical functions must be developed in a form that does not interfere with and, if possible, enhances the tactical needs. One example of this synergy would be the dual use of a pedometer for both location and metabolic estimates.

The objective of this project is to provide MRMC with an evaluation of current technology that might be used in Warrior Medic and a demonstration of how simulation can be used to guide future development. Specific objectives are:

1. Collect data using the LW DRM under a variety of activities.
2. Develop mathematical models for normal and traumatic events.
3. Use the model to evaluate a conceptual system for detecting trauma.

4. Define a research plan for the model required to meet WM needs.

1.5 Work Performed and Organization of the Report

The first part of the project dealt with the evaluation of PointMan® DRM. This task acquired, adapted, and evaluated the PointMan Dead Reckoning Module as a source of motion data that could be used for WM purposes. It included the following subtasks:

Task 1.1: Acquired DRM and recording software DRMHost.

Task 1.2: Acquired the modified version DRM-G10 which allows the direct output of analog signals.

Task 1.3: Pendulum rocking tests and airbag tests were performed to evaluate the possibility of using DRM or the sensor inside the DRM to distinguish normal and traumatic events.

Section 2.0 gives the details of tasks 1.1-1.3. Results suggest that while the DRM is adequate for normal events, the sensor inside the DRM might be able to capture traumatic events. Therefore, further examination of the distinguishing capability of DRM-G10 was performed.

Task 1.4: Manikins and representative backpack were obtained

Task 1.5: Designed a surrogate test to simulate the human response to bullet impact

Task 1.6: Collected trauma response data with surrogates.

Task 1.7: Collected normal response data with volunteers.

Task 1.8: Tested the feasibility of using DRM to obtain physiological data.

Task 1.9: Assessed the discrimination potential of the DRM.

Detailed results and analysis are given in section 3.0., which suggest that the ballistic detection might be possible, however, the current system will have to be modified.

In the second part of the project, mechanical models were developed to overcome the limitations of experiment work.

Task 2.1: Developed a traumatic response model.

Task 2.2: Developed a simple kinematic model of human locomotion

Task 2.3: Models were used with experiment data to extrapolate the experimental results

Section 4.0 gives the details of the models. Simulation results suggest that modeling, when combined with experiment data, offers means to deal with problems which cannot be solved solely by experiments.

Section 5.0 summarizes the research findings and makes suggestions for future work.

2.0 Evaluation of PointMan® DRM

This task acquired, adapted and evaluated the PointMan Dead Reckoning Module (DRM) as source of motion data that could be used for Warrier's Medic purposes. The discriminating capability of DRM and its modified version DRM-G10 were tested.

2.1 PointMan® DRM and DRM-G10

The PointMan Dead Reckoning Module is a miniature, self-contained, electronic navigation unit that provides the user's position relative to an initialization point (Point Research Corporation, 1998). It contains a three-axis accelerometer, three-axis magnetometer, and pressure and temperature sensors. When mounted inside the LW backpack, it works as an elaborate pedometer to calculate the soldier's motion on foot and serves as a backup to the GPS system.

The DRM, when used as a navigation device, reports location and orientation at a 5 Hz rate. This rate is too slow for monitoring purposes. But internally, the three axis accelerometers are being sampled at 50 Hz. Point Systems provided the software DRMHost to allow the accelerometer measurements to be transmitted and recorded externally (Marshall, 1998). In use, the DRM is connected to an external computer system through a cable. The software records real time acceleration data at a 50 Hz rate. The data are saved in ASCII format.

The accelerometers have a rating of ±10 G's full scale. However, the filtering limits the full scale to ±2 G, which was found to be too small to detect any traumatic events. Therefore, a contract was made with Point Systems to modify the DRM so that the analog acceleration signals can be output directly (Bellin, 1998). The modified DRM is named as DRM-G10. In experiments, an external computer using LabView® picked up the analog signals and saved data in ASCII format. The sampling rate was adjusted by changing the parameters in the software.

2.2 Pendulum Rocking Test: Evaluating DRM During Regular Event

The accelerations measured by the DRM were verified in pendulum rocking tests. The pendulum used in the tests is shown in Figure 1, which has the length of 0.938 meter, the radius of 0.152 meter and weights about 34 kilograms. In the tests, the DRM was mounted onto the bottom of the pendulum. The pendulum was set at an initial angle and was allowed to swing freely. The acceleration data were recorded and compared with the analytical solution.

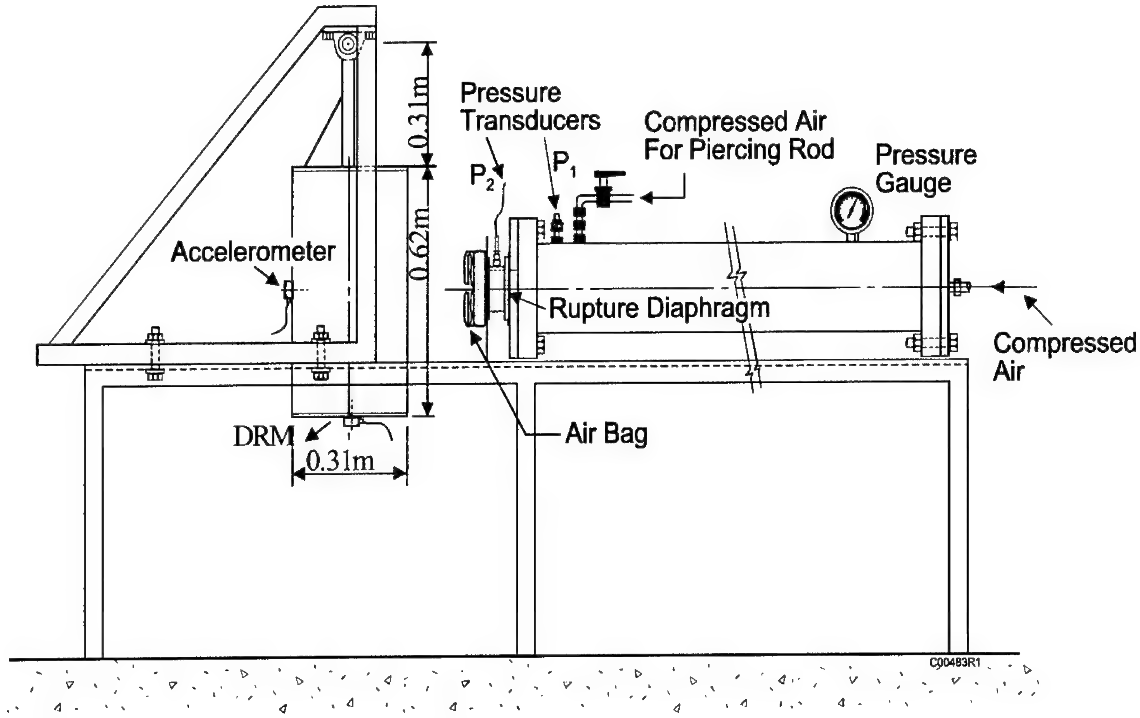

Figure 1 Schematic of pendulum rocking test and air bag test setup

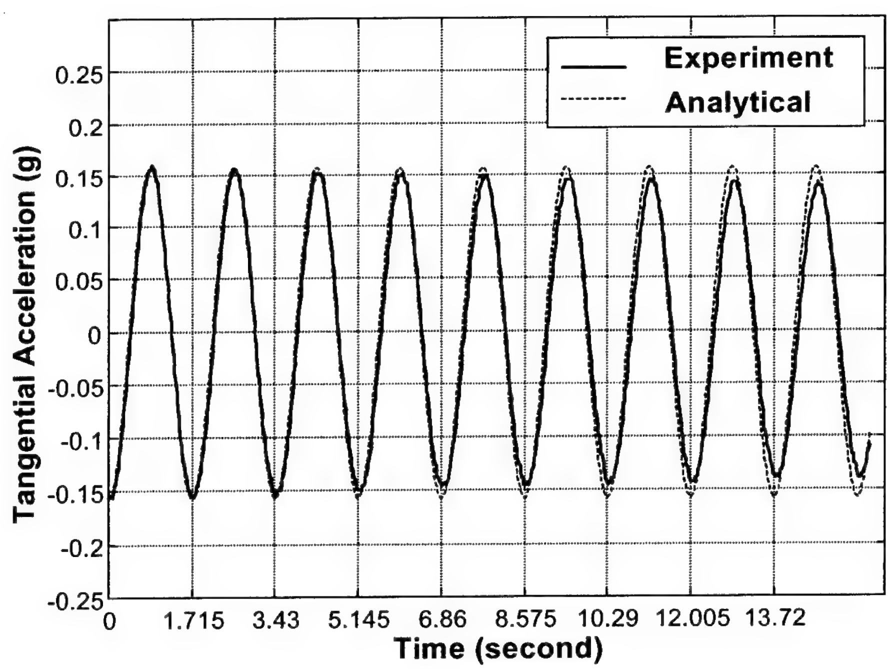

Figure 2 Measured acceleration versus analytical solution in the pendulum rocking test

Figure 2 shows an example of the results when the pendulum was initially set at about 15 degree. The measured data matched very well with the analytical solution. However, the measured acceleration diminished with time. This was due to the damping in the connection of the pendulum and its support. The damping effect was not taken into account in the analytical solutions. The sampling rate of 50 Hz of the DRM was sufficient to catch the response of the pendulum, which had a natural period about 1.7 seconds.

2.3 Airbag Test: Evaluation DRM During Traumatic Event

Since the DRM samples at the rate of 50 Hz, it is not able to detect any signal lasting less than 20 millisecond. Therefore, in order to evaluate the potential of DRM during traumatic events, impact loads lasting relatively longer is needed. The Jaycor airbag testing facility (Figure 1) developed for DOT provides such an impact. The test setup was designed to simulate the blunt airbag impact to a thorax model. Usually it delivers a blunt impact load lasting 50 miliseconds or longer.

During the tests, compressed air was filled inside the tube. Air bag was separated from the tube by a diaphragm. By rupturing the diaphragm, the airbag was inflated and hit the pendulum in front of the airbag. The magnitude and the duration of the impact load were adjusted by changing the tube pressure of compressed air and the standoff distance between the airbag and the pendulum.

In order to verify the accelerations measured by DRM and DRM-G10, a dynamic accelerometer was rigidly mounted onto the pendulum to measure the tangential acceleration during the impacts. This accelerometer can measure accelerations up to about 200 G. DRM and DRM-G10 were mounted onto the bottom of the pendulum. In addition, a high-speed camera was used to record the motion of the pendulum.

Figure 3 shows a representative test result. Tube pressure was about 40 Psi (or 0.276 MPa). The standoff distance between the airbag and the pendulum is zero. The sampling rate of the analog signal output of the accelerometer and DRM-G10 was 50 kHz. The accelerations measured by the accelerometer and DRM-G10 were processed to remove high frequency noises.

It is shown in the Figure 3 that the impact load lasted about 75 miliseconds. The peak acceleration was much larger than 10G, which is the full scale of DRM-G10. Its scale limited the acceleration measurement from DRM-G10. However, it did capture much of the response. This is further confirmed in Figure 4, which shows comparison of the rotational angles measured from the high speed movie, integrated from the dynamic accelerometer acceleration data and integrated from the DRM-G10 acceleration data. Dynamic accelerometer captured the actual motion very well, while DRM-G10 also captured much of the actual motion.

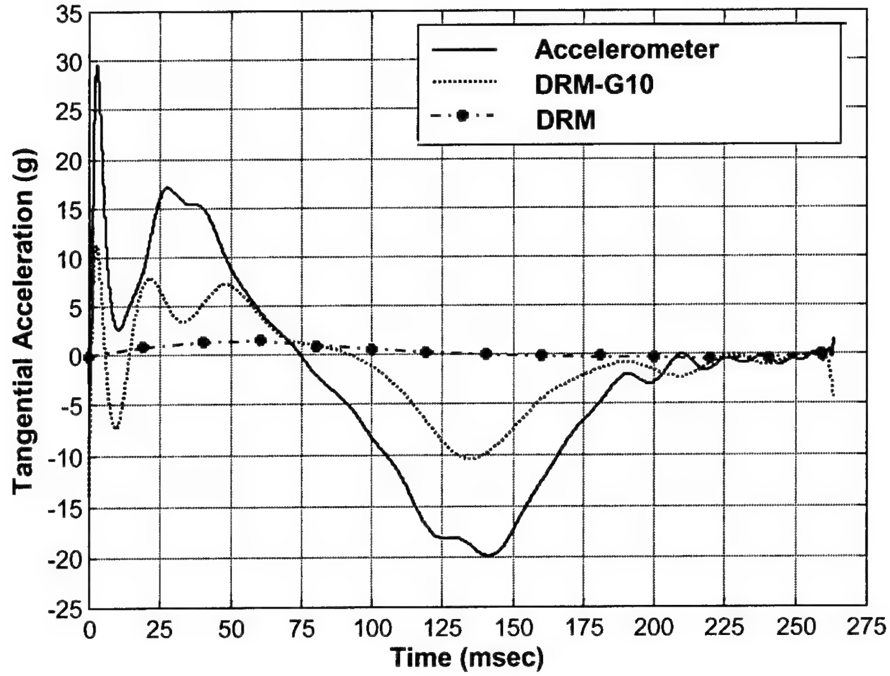

Figure 3 Accelerations measured in an airbag test

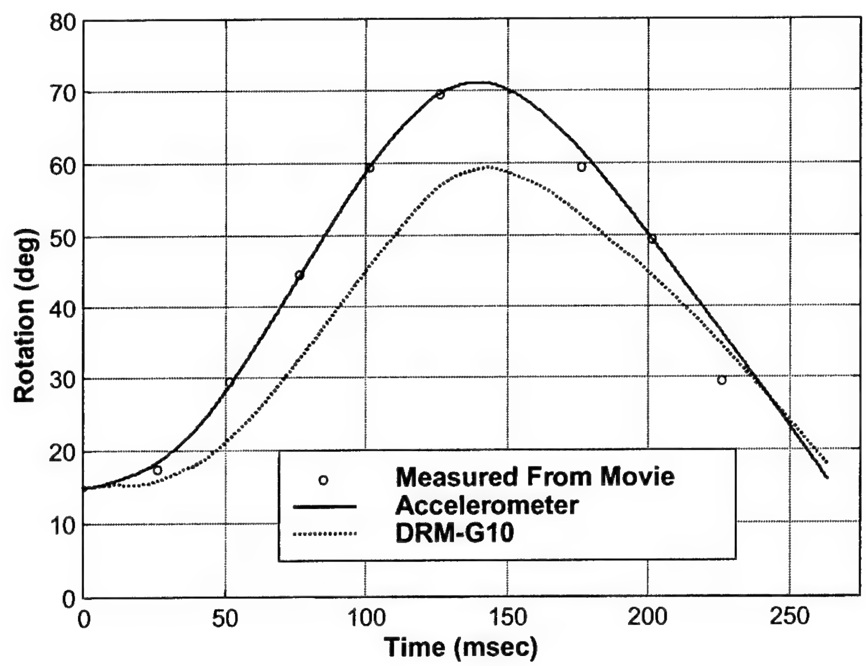

Figure 4 Verification of acceleration data by comparing rotational angles

The original DRM, on the other hand, failed to capture the impact. From Figure 3, although it also gave a few points of relatively high acceleration, the magnitude of the acceleration was about 2G,

which was too small to make any sensible judgement. The accelerations measured by DRM were completely distorted, therefore, rotational angles calculated from the DRM acceleration are meaningless and are not given here.

2.4 Summary

Several preliminary conclusions are made from these test results:

- DRM seems to work well for regular events
- DRM with digital filtering is unlikely to capture traumatic events
- The accelerometers used in the DRM (DRM-G10) may be able to characterize traumatic events

3.0 Traumatic, Normal and Physiological Acceleration Measurement

The previous section has shown that the DRM works well for normal events and DRM-G10 may be able to capture the traumatic events. This section attempts to determine if the DRM may distinguish between normal events and traumatic events commonly experienced in real situations. The primary problem under investigation is whether it is possible to determine from DRM data if a soldier is performing normal activities such as running, jumping or has been shot.

A surrogate experiment was setup where a manikin carried a backpack similar to LW pack and was impacted with a bullet surrogate. DRM-G10 measured the acceleration at the different spots on the dummy's body or in the pack. DRM and DRM-G10 were also used to measure the normal and physiological acceleration data when a real person was doing normal activities or was at rest. These data were compared to determine the possibility of using DRM to detect ballistic impact.

3.1 Normal Response

In order to distinguish the traumatic events from normal events, the normal response data must be collected and studied. Several types of locomotion including hopping in place, high jumping continuously, high jump and sudden stop, and running in place were experimented with a human subject. Running and walking were not been tested because the collection of acceleration data requires cable connection to a computer. Current facility is not capable of handling locomotion involves a traveling distance longer than the length of a cable (5 to 10 meters). Figure 5 - 7 give the representative accelerations, velocities and power spectrums of these types of locomotion.

These figures show that human locomotion usually involves peak acceleration around 2 g and velocity changes between 0.5 to 1.0 meter per second. The characteristic loading time is greater than 100 millisecond. The frequency range of the response is below 20 Hz.

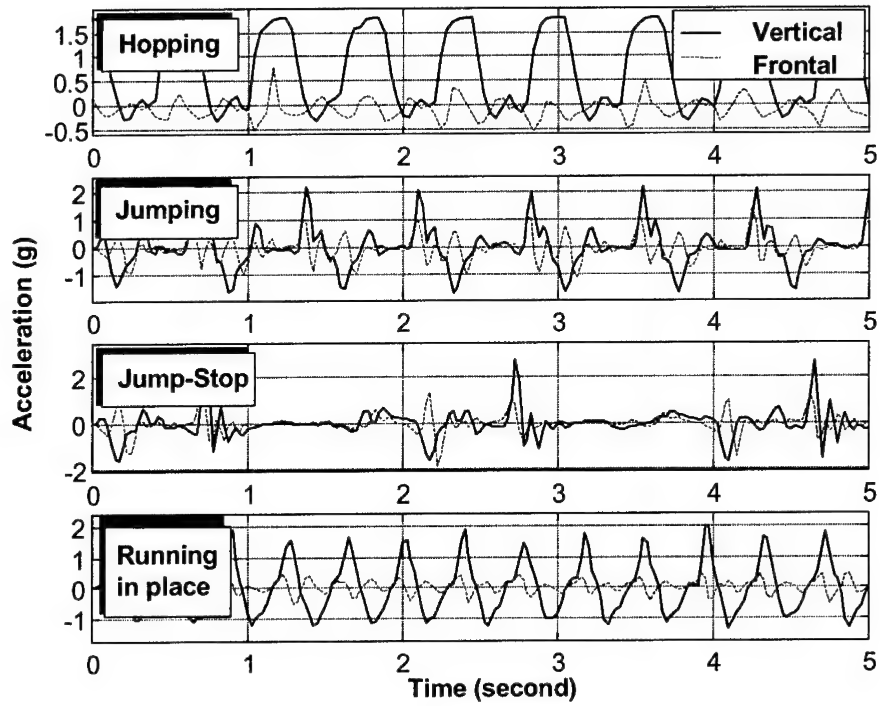

Figure 5 Accelerations of different types of locomotion

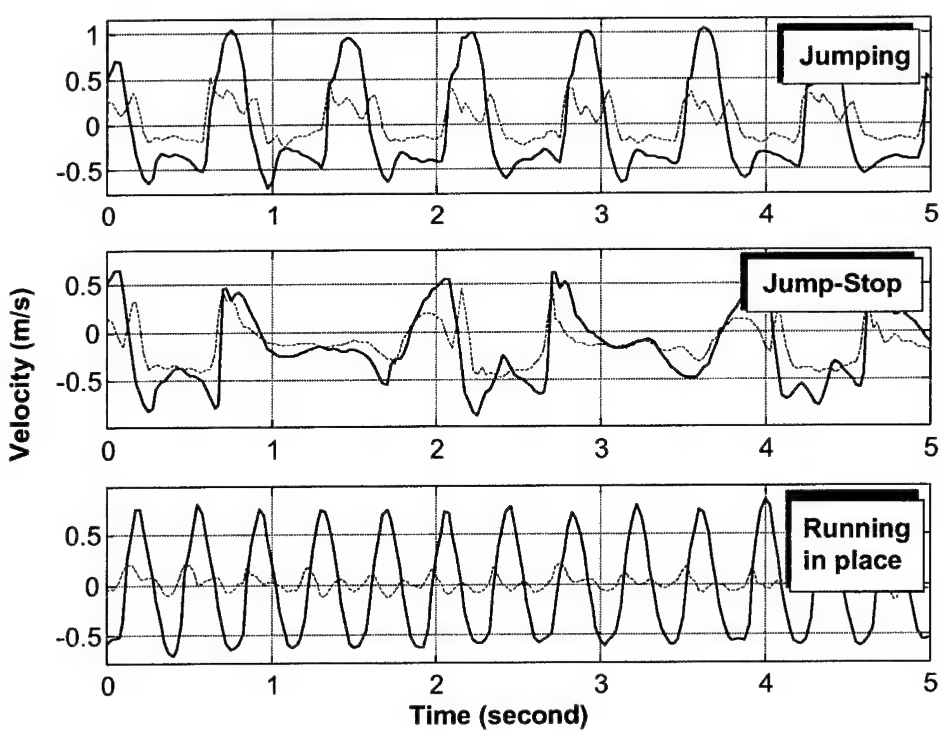

Figure 6 Velocities of different types of locomotion

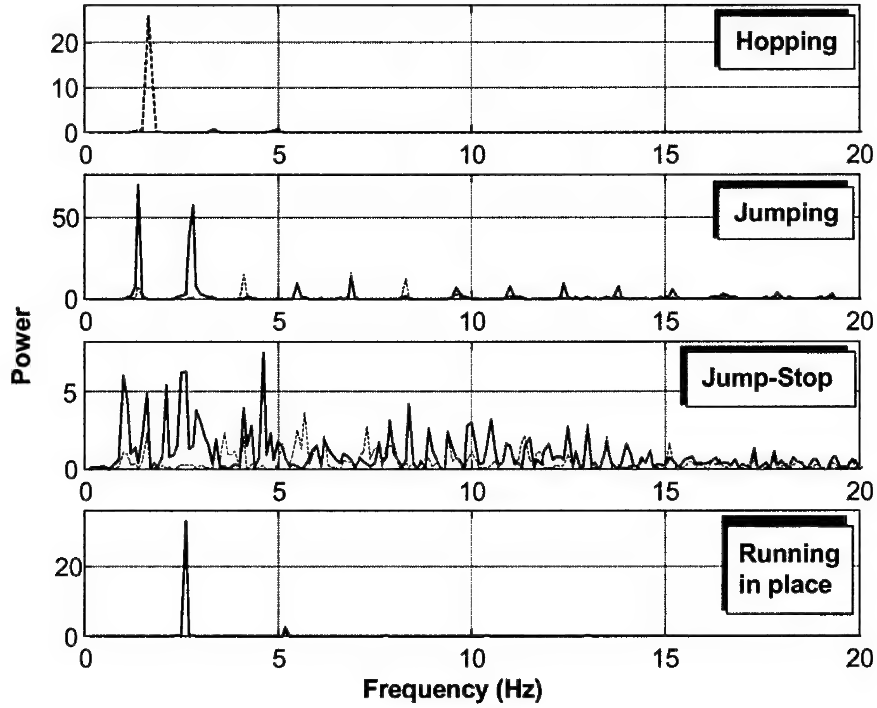

Figure 7 Power spectrum of different types of locomotion

3.2 Traumatic Response of Surrogates

3.2.1 Setup of surrogate experiment

Dummies were supplied by Walter Reed. Since the LW pack was not available, a GI-Style large A.L.I.C.E. pack and an A.L.I.C.E. LC-2 rucksack frame purchased from the U.S. Calvary were used to provide a representative configuration. Figure 8 shows the way the backpack was mounted on the dummy. As can be seen in the figure, the backpack was attached tightly to the frame. The frame was in direct contact with the back and waist of the dummy. The wide kidney belt and padded shoulder straps attached the frame tightly to the dummy and distributed the load from the backpack.

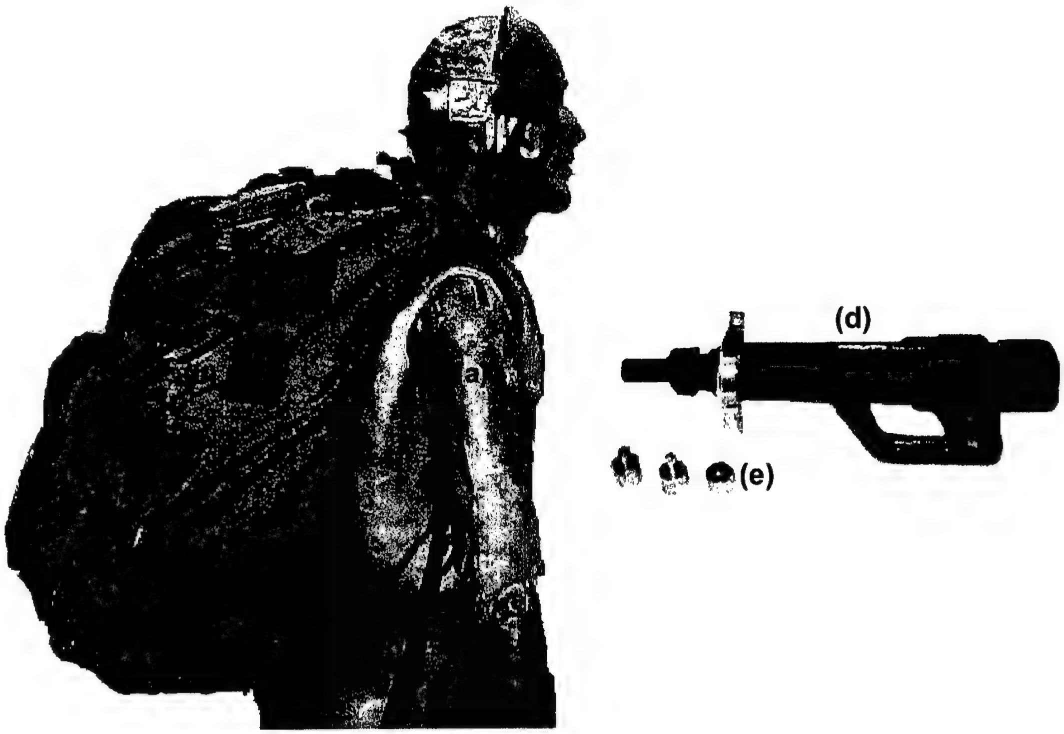

Figure 8 Setup of surrogate ballistic impact test

(a) Dummy; **(b)** GI-Style large A.L.I.C.E. Pack (no straps) holds approximately 3,800 cubic inches; **(c)** A.L.I.C.E. LC-2 rucksack aluminum frame with a wide kidney belt and padded shoulder straps; **(d)** Modified nailgun to deliver ballistic impact load; **(e)** Steel nail shot into steel block, which transfers the momentum to the dummy

Table 1 Bullet Mass, Impact Velocity and Momentum as Specified for Ballistic Resistance Test Defined by National Institute of Justice

Type	Bullet Caliber	Mass (grains)	Velocity (m/s)	Momentum (N.s)
I	.22 long rifle high velocity	40	320	0.83
	.38 round-nose lead	158	259	2.65
II-A	.357 jacketed short-point	158	381	3.90
	9-mm full metal jacket	124	332	2.67
II	.357 jacketed short-point	158	425	4.35
	9-mm full metal jacket	124	358	2.88
III-A	.44 magnum lead semi-wadcutter gas-checked	240	426	6.64
	9-mm full metal jacket	124	426	3.43
III	7.62 mm full metal jacket	150	838	8.15
IV	.30-06 armor-piercing	166	868	9.34

The load delivered by a bullet shot on a human body usually carries a momentum of about 1 to 10 Newton-second (Table 1) and lasts less than 1 millisecond. For the repetitive use of the dummy and the safety of experiment, it is not possible to shoot the dummy with a real weapon. Therefore, a construction nail gun was modified to generate a non-destructive force similar to that of a bullet (Figure 8(d),(e)). In experiments, a cylindrical steel block was placed inside the chamber of the nail gun. The nail gun was placed directly in front of the part on the dummy to be shot. When the gun was fired, a nail was shot and hit the steel block in the chamber. The steel block then hit the dummy and transferred the momentum to the dummy. This device is non-destructive and easy to use.

The momentum of the steel block and the loading duration were measured by firing the gun against a force plate. The results are given in Figure 9 and Table 2. The momentum is about 8 N.s while the loading time is about 1 millisecond, which matched well with the load of a real bullet. The measured force was a high frequency signal with the dominant frequency about 750 Hz. Table 2 also suggests that the repeatability of the experiments was good.

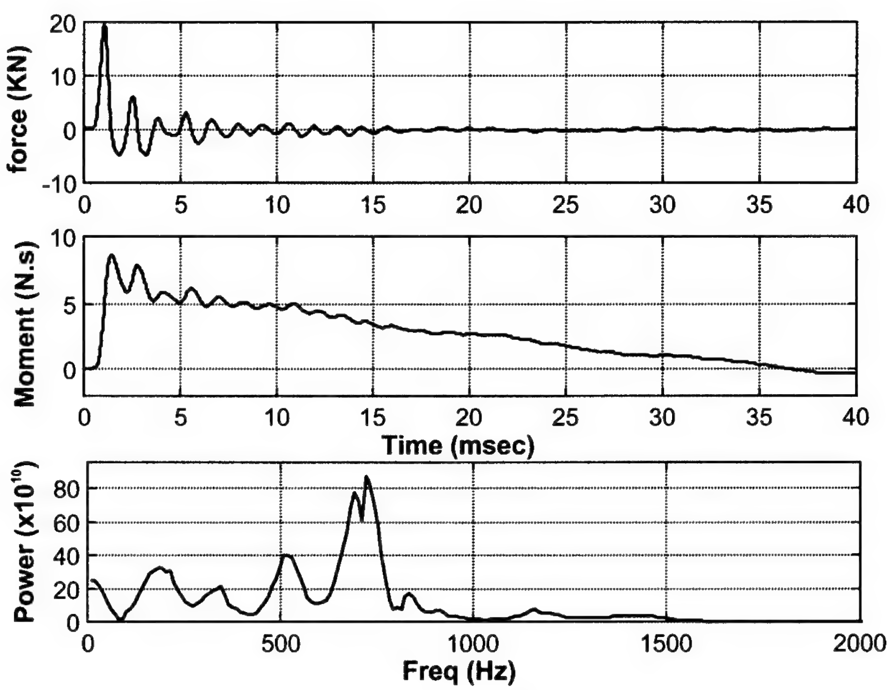

Figure 9 Test Results when the Nail Gun Fire against a Force Plate

Table 2 Force and Momentum Delivered by the Nail Gun

No.	Description	Peak Force (KN)	Moment (N.s)	Duration (ms)	Significant Freq. (Hz)
1	Nail-Gun shoot directly against force plate	20	8.1	0.9	10-800
2		17	7.5	1.0	10-1000

3.2.2 Test Results

A total of ten experiments was performed. In the tests, the nail gun shot against one side of the dummy. The accelerations were measured by DRM-G10 on the other side of the dummy, on the frame and inside the backpack. To further study the effect of connection between the backpack, the frame and the dummy, a hard rubber layer or a cushion layer was also put between the frame and the DRM-G10 and between the frame and the dummy. Detailed description of each experiment is given in Table 3. Some characteristic values are used to describe the responses. They are peak acceleration (**A_m**), peak velocity (**U_m**), characteristic response time (**ΔT**), and significant frequency range (**f_{sig}**). Characteristic response time is the time period between the time when the acceleration starts to increase from zero till it drops back to zero. Significant frequency range (**f_{sig}**) is the frequency range that can be seen clearly from the power spectrum plot.

Table 3 Summary of the Nail Gun Shooting Dummy Test Results

No.	Description	A_m(g)	U_m(m/s)	ΔT(ms)	f_{sig}(Hz)
1	Sensor (DRM-G10) was taped tightly to the skin of the manikin	8.5	0.35	4	10-200
2		8.0	0.35	7	10-150
3	Sensor was attached to the frame	2.0	0.14	16	10-70
4		2.1	0.16	14	10-80
5	Sensor was attached to the frame with a layer of hard rubber	1.4	0.12	17	10-80
6		1.5	0.10	16	10-65
7	Sensor was mounted in the backpack	0.9	0.17	27	10-30
8		1.0	0.18	25	10-28
9	Sensor was mounted in the backpack; a cushion layer was put between frame and dummy's torso	1.0	0.19	25	10-30
10		0.8	0.18	32	10-25

Figure 10 to Figure 12 give examples of the detailed acceleration history, velocity history and power spectrum of the test results. The results show a clear pattern: when the placement of the sensor was further away from the dummy, peak acceleration diminished; peak velocity decreased and significant frequency range dropped.

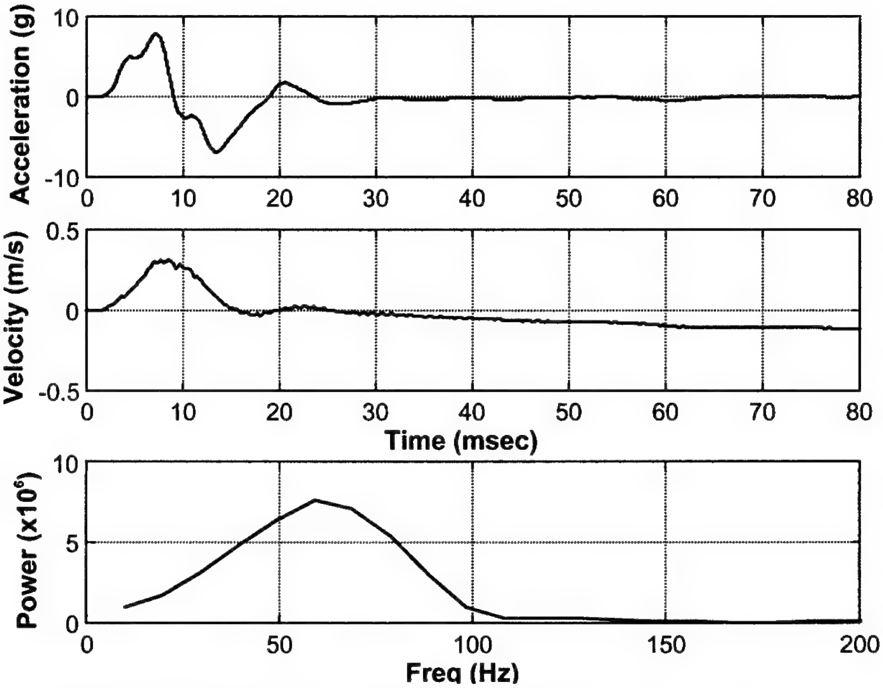

Figure 10 Acceleration and velocity on the dummy torso

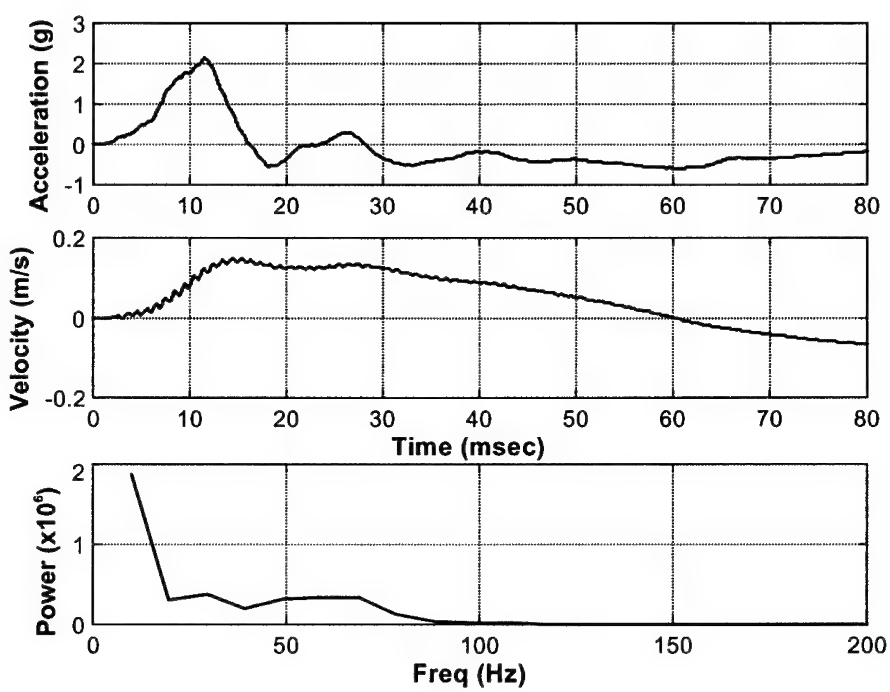

Figure 11 Acceleration and velocity on the frame

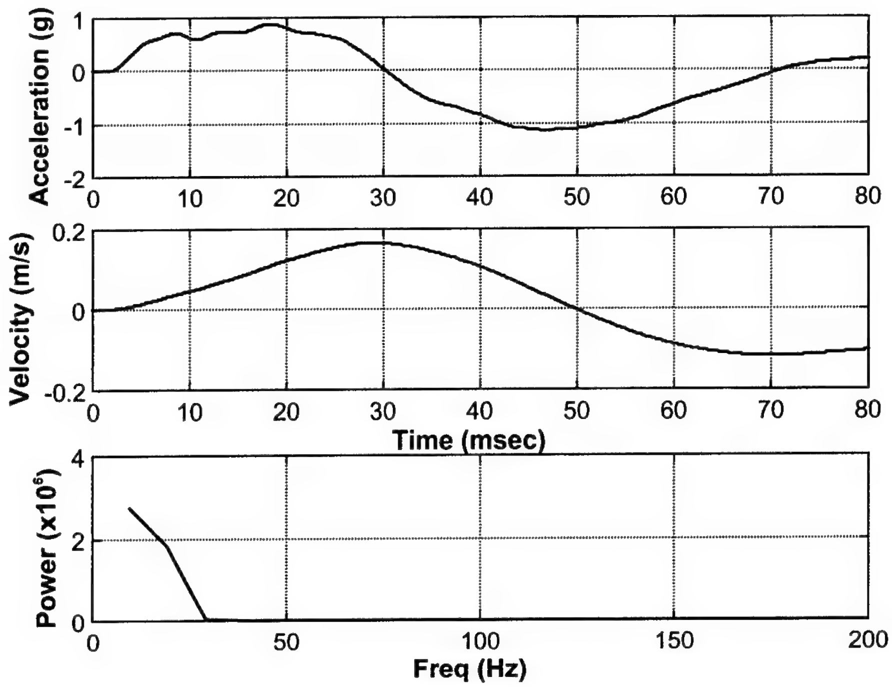

Figure 12 Acceleration and velocity inside the backpack

Figure 13 compares the accelerations commonly experienced during locomotion and the accelerations measured on the manikin, on the frame and inside the backpack. Common locomotion can lead to peak acceleration of about 2g with a loading time longer than 100 milliseconds. During a traumatic event as used in the experiments, when the sensor was taped tightly to the skin of the manikin, short-duration (7 miliseconds), large (8 g) acceleration was seen. This event was clearly very distinct, both in amplitude and duration, from locomotion data given in the following section. When the sensor was attached to the frame of the backpack, the acceleration peak was only 2 g, but the duration was 16 milliseconds. Its duration, but not its amplitude might distinguish this event. When the sensor was placed in the backpack, the signal was less than 1 g with duration of 28 milliseconds. It is unlikely that this could be distinguished from other normal, violent events.

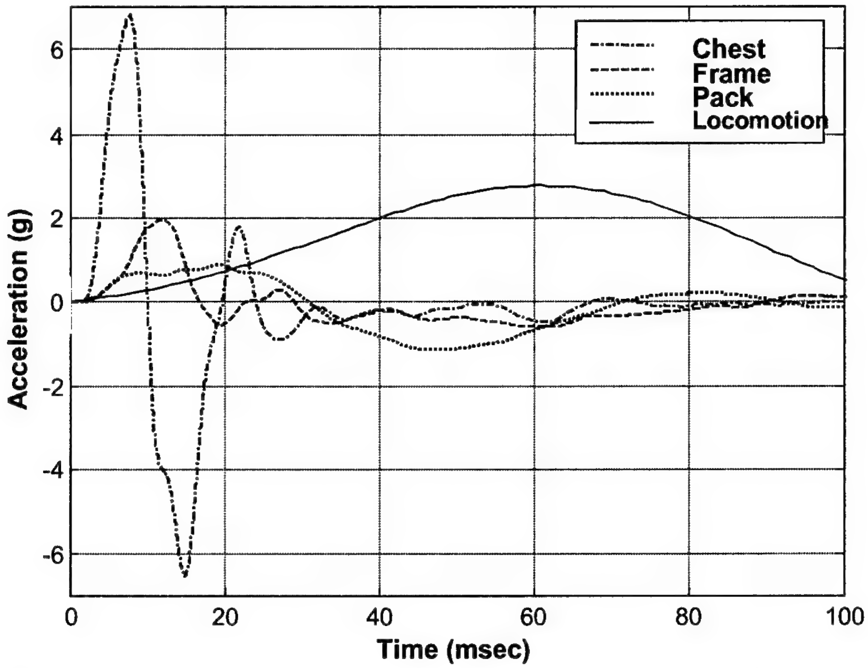

Figure 13 Comparison of accelerations during normal and traumatic events

However, the velocity resulted from bullet impact was less than 0.35 m/s which was far smaller than the velocity a human being usually reaches during regular locomotion. The peak acceleration is sensitive to noise and requires a very high sampling rate to get a good estimation, therefore, it is not a good and reliable criterion in distinguishing different events. This poses a difficulty in choosing the right criteria, which requires further study in future.

Another point worthy mentioning is that the loading duration of the bullet impact was only about 1 millisecond, while the characteristic response duration at the sensor is 7 milliseconds when the sensor is taped tightly to the skin on the other side of the dummy. This suggests that the dummy itself did not act like a rigid body, rather it involved significant flexibility and damping. It will be necessary to understand whether a real human being will demonstrate similar degree of flexibility and damping. This should also be a concern in future research.

3.3 Physiological Response of Human being

From previous experiment results, it seems that physiological response may also be necessary in the detection of injury. A few experiments were done to see if the DRM-G10 could be used to detect vital physiological data such as heart beat. The DRM-G10 was attached tightly on the chest of a human subject. The subject was at rest and the acceleration data were recorded at a sampling rate of 1000 Hz. Figure 14 shows the result after some filtering. The DRM-G10 did catch the heat beats, which

demonstrated as peaks in the acceleration history curve. However, the magnitude of the acceleration was too small to be detected if the subject was not at rest.

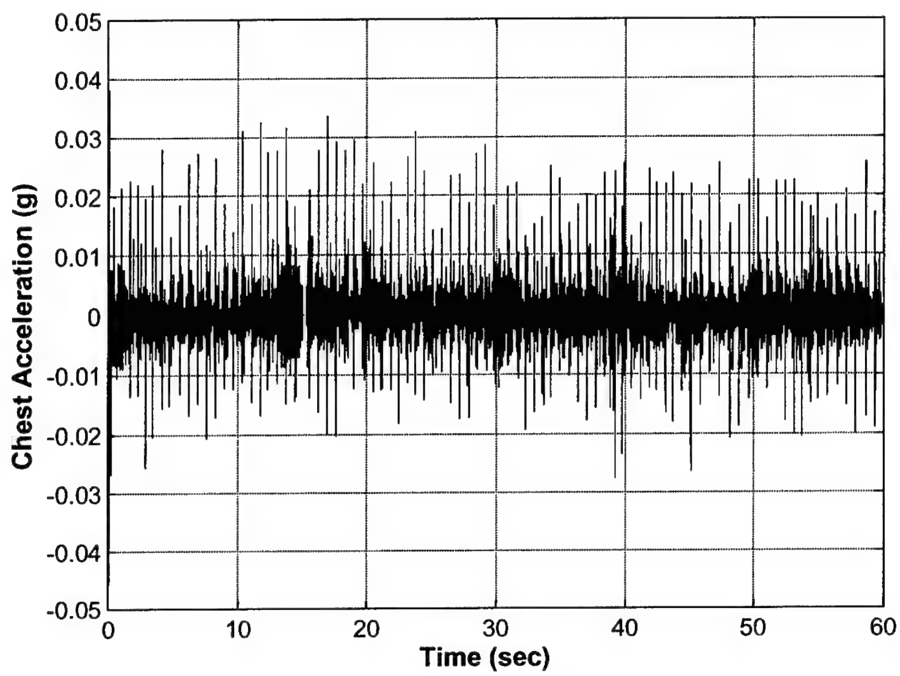

Figure 14 Chest acceleration measurement when human subject is at rest

3.4 Summary

The findings are encouraging: the accelerometers are sensitive enough and the signal is still significant on the other side of the body, maybe even in the frame.

For ballistic detection to be possible, however, the current system will have to be modified. The full range of the accelerometers will have to be used and sampled at a high rate. The sensor will have to be more tightly coupled to the body than provided by the backpack. The frame might be OK, body-mounted even better. Finally, the detection scheme will have to take advantage of the short duration to distinguish a traumatic event. Amplitude will not be enough.

There are still a number of issues to be resolved. First, it should be attempted to understand if the manikin responds like a person. Second, more data are needed from a wider range of traumatic events (bullet to the head) and normal events (riding in a car). Third, the sensor placement and mounting is critical to the observed response and must be selected both for the response and for the practicality of implementing in LW. Furthermore, a robust discrimination algorithm must be developed and tested.

- Finally, if properly designed, accelerometers might provide important physiological information, which can help the detection of sudden traumatic events. More research is required in the study of the physiological sensors.

Manikin and volunteer tests provide critical validation data for a limited number of conditions. Biomechanical modeling in capturing the observed responses, on the other hand, offers a means to try all sensor locations and trauma conditions. The success of modeling will help the systematic development of the best detection system.

4.0 Modeling Human Response in Traumatic and Normal Events

The previous section provides data on particular, laboratory-generated mechanical responses. These data give the fundamental information in evaluating the capability of DRM. However there are some limitation of the experimental techniques. First, with current facilities and equipment, it is difficult to measure the acceleration at different locations on the body at the same time. This information is important in the design of the mounting of DRM. Secondly, the data measured in the laboratory during a certain experiment cannot be generalized to different person or different loading conditions. And finally, since the bullet-shooting test cannot be performed on real person, how well the response of a dummy matches that of a person cannot be simply answered by experiments. To overcome these limitations, mechanical response models are needed. The models will use some experiment data as part of the input and predict the response of a human being under various conditions.

This section develops simple models to simulate human response to traumatic events and normal activities.

4.1 Modeling Human Response to Traumatic Events

During traumatic events, an impulsive load lasting a short period of time hits a person. Usually, the duration of the load is so short that the voluntary reaction of the person is negligible. Articulated models can simulate the person's response. These models are based on rigid-body dynamics using Euler equations of motion with Lagrange-type constraints (Cheng *et al*, 1998). A human is modeled as a set of segments, which represent the different parts of the body. Each segment is rigid and possesses mass and moments of inertia. Various types of joints connect the segments and form an open loop structure (tree-structure). The relative rotations of the neighboring segments are resisted by torques at the joints. Given the dynamic loads on the human body, the motion of the body and its parts can be simulated by a forward dynamic analysis.

A model was developed using rigid dynamics software Working Model 3D® (Knowledge Revolutionary, 1998), a commercial product of Knowledge Revolutionary. The body property-generating program GEBOD® (Cheng *et al*, 1994) was used to generate the geometrical, mass, inertia and joint mechanical data. Situations like a person hit by the explosion of an airbag and hit by a bullet were simulated. The magnitude and the duration of the load used in the simulations were estimated from experiments.

4.1.1 Configuration and Reference Coordinate Systems

As can be seen in Figure 15, the specific model configuration adopted in this study involves 15 body segments. They consist of head, neck, upper torso (thorax), center torso (abdomen), lower torso

(pelvis), upper arms, lower arms, upper legs, lower legs and feet. The lower arms are combinations of the forearms and hands. The segments are assigned mass and moments-of-inertia and are coupled together by 14 joints representing the physical joints of the human body such as pelvis, waist, neck, hips, knees, ankles, shoulders and elbows.

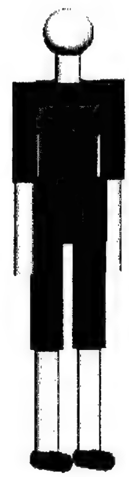

Figure 15 An articulated human body

Various reference coordinate systems are used for the convenience of model development and analysis. The specification of each reference system requires an origin and three rotation angles, yaw, pitch and roll or precession, nutation and spin, as depicted in Figure 16. Yaw (y), pitch (p) and roll (r) are consecutive body fixed rotations about the Z, Y, and X-axes. While precession (ϕ), nutation (θ) and spin (ψ) are defined as the rotations about the Z, X, and Z axes respectively.

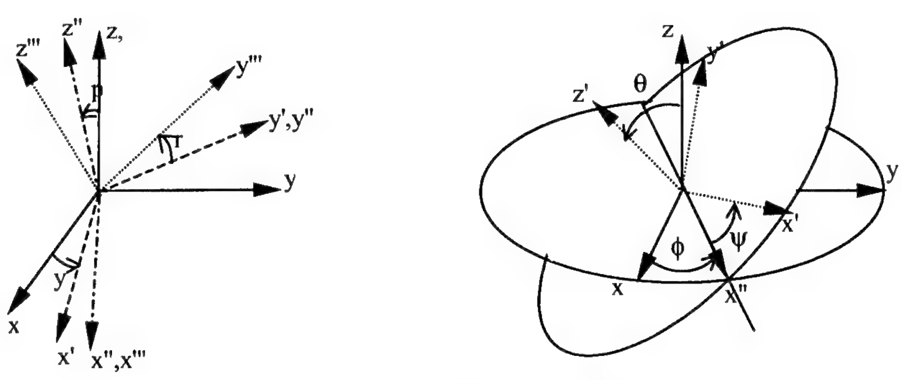

Figure 16 Definition of rotational angles
(a) Yaw, Pitch, Roll; **(b)** Precession, Nutation, Spin

Inertia reference system is used as the global coordinate system, which means the coordinates of its origin are zero and all other coordinate systems are specified with respect to this system. In terms of a standing man, the positive Z_G direction is pointing downward, as shown in Figure 17(a). The lateral direction pointing from the standing man's left side to his right side is taken as the positive X_G direction and by the right hand rule, the positive Y_G direction is in the backward direction.

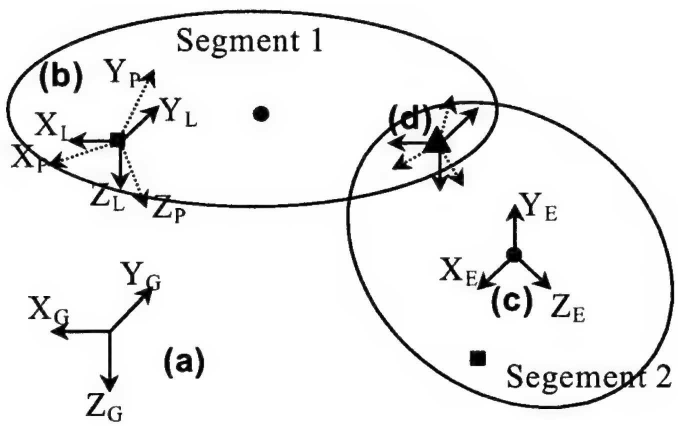

Figure 17 Reference coordinate systems
(a) Global coordinate system; **(b)** Local coordinate system and principal moment of inertia axes of segment 1 at the segment's center of mass; **(c)** Contact geometry coordinate system of segment 2 at the segment's geometric center; **(d)** Joint coordinate systems

Each body segment has a **local coordinate system** (marked with subscript "L" in Figure 17(b), which has its origin at the segment mass center. The orientation of the local reference system can be arbitrary. The convention used here is to choose the axes so that, when the body is in an upright standing position with arms at the side, the Z_L axis is downward, the X_L axis is to the body's right and Y_L axis is to the back. **The principal moment of inertia axes**, subscripted with "P" in Figure 17(b), are specified with respect to the local reference system.

A simple contact geometry is associated with each segment and is used to represent the physical appearance of the segments. It is the outer surfaces of the segment, and can interact with the environment by contact. There is no direct association of the segment inertial properties and the shape of the contact geometry. The **contact geometry coordinate system** as shown in Figure 17(c) is also specified with respect to the local reference system.

In order to calculate joint torques, it is necessary to define two **joint coordinate systems** for a joint; one rigidly attached to each of the two segments that are connected by the joint, as shown in Figure 17(d). The orientations of the joint coordinate systems are specified by rotation angles from the local reference systems of both segments. Once the two joint coordinate systems are defined, they are fixed in the corresponding segments and unable to move relative to the segments.

4.1.2 Segment and Joint Data

The mass and moments of inertia for the body segments and the dimension of the associated contact geometry were generated using GEBOD® . The data used by Kaleps (1979) were also referred to. The developed model has a weight of about 75 kilograms and a height of about 1.8 meters. Based on these two parameters, it is classified in the 95th percentile of the adult U.S. males.

Except for the head, which is represented by a sphere, all the segments are represented by cylindrical contact geometry with z axis aligned to the longitudinal directions. To simplify the model, it is assumed that segment local coordinate system coincides with the contact geometry reference system. It is also assumed that principal moments of inertia axes are aligned with the local reference system. The dimensions of the segments and the positions of the centers of the segments (in global coordinate system) are given in Table 4. The mass and inertia properties of the segments are given in Table 5.

Table 4 Geometry and the Positions of the Segments

Segment	Name	Contact Geometry			Geometric Center		
		Shape	Radius	Height	X	Y	Z
1	Lower torso	Cylinder	0.1500	0.2500	0.0000	0.0000	0.7152
2	Center torso	Cylinder	0.1150	0.3800	0.0000	0.0000	0.5196
3	Upper torso	Cylinder	0.1350	0.2100	0.0000	0.0000	0.3048
4	Neck	Cylinder	0.0500	0.2000	0.0000	0.0000	0.1616
5	Head	Sphere	0.1000	N/A	0.0000	0.0000	0.0000
6	Right upper leg	Cylinder	0.0625	0.6000	0.0894	0.0000	0.9621
7	Right lower leg	Cylinder	0.0480	0.5000	0.0894	0.0000	1.4198
8	Right foot	Cylinder	0.0400	0.2400	0.0894	-0.0427	1.7053
9	Left upper leg	Cylinder	0.0625	0.6000	-0.0894	0.0000	0.9621
10	Left lower leg	Cylinder	0.0480	0.5000	-0.0894	0.0000	1.4198
11	Left foot	Cylinder	0.0400	0.2400	-0.0894	-0.0427	1.7053
12	Right upper arm	Cylinder	0.0480	0.4000	0.1849	0.0000	0.3960
13	Right lower arm	Cylinder	0.0400	0.4500	0.1849	0.0000	0.7396
14	Left upper arm	Cylinder	0.0480	0.4000	-0.1849	0.0000	0.3960
15	Left lower arm	Cylinder	0.0400	0.4500	-0.1849	0.0000	0.7396

Segment	Name	Weight (kg)	Moments of Inertia		
			X	Y	Z
1	Lower torso	18.121	0.1650	0.1706	0.1996
2	Center torso	18.393	0.1966	0.2779	0.2034
3	Upper torso	11.793	0.0813	0.1345	0.1356
4	Neck	2.758	0.0027	0.0027	0.0023
5	Head	5.638	0.0260	0.0226	0.0158
6	Right upper leg	10.891	0.2034	0.2034	0.0554

7	Right lower leg	4.327	0.0734	0.0734	0.0079
8	Right foot	1.501	0.0056	0.0056	0.0011
9	Left upper leg	10.891	0.2034	0.2034	0.0554
10	Left lower leg	4.327	0.0734	0.0734	0.0079
11	Left foot	1.501	0.0056	0.0056	0.0011
12	Right upper arm	3.080	0.0192	0.0192	0.0036
13	Right lower arm	2.422	0.0340	0.0340	0.0019
14	Left upper arm	3.080	0.0192	0.0192	0.0036
15	Left lower arm	2.422	0.0340	0.0340	0.0019

Two types of joints are used in the model: **ball-and-socket joints** are used for pelvis, waist, neck, hips and shoulders while **pin joints** are used for elbows, knees and ankles. In a ball-and-socket joint, a flexure angle (around X) and a twist angle (around Z) characterize the rotation of the joint. In relation to Euler angles, flexure angle is nutation and twist angle is the sum of precession and spin. A ball joint has two degrees of freedom. In a pin joint, only flexure (rotation around X) is allowed. Positions of a joint are defined with respect to the segments it connects in their local reference systems. They are transformed into the global coordinate systems and are listed in Table 6.

Table 6 Joint Position and Types

Joint	Name	Segments	Position			Joint type
			x	y	z	
1	Pelvis	1,2	0.0000	0.0000	0.6174	B&S
2	Waist	2,3	0.0000	0.0000	0.4122	B&S
3	Neck pivot	3,4	0.0000	0.0000	0.2332	B&S
4	Head pivot	4,5	0.0000	0.0000	0.0808	B&S
5	Right hip	1,6	0.0894	0.0000	0.7386	B&S
6	Right knee	6,7	0.0894	0.0000	1.2184	B&S
7	Right ankle	7,8	0.0894	0.0000	1.6497	B&S
8	Left hip	1,9	-0.0894	0.0000	0.7386	B&S
9	Left knee	9,10	-0.0894	0.0000	1.2184	Pin
10	Left ankle	10,11	-0.0894	0.0000	1.6497	Pin
11	Right shoulder	3,12	0.1849	0.0000	0.2578	B&S
12	Right elbow	12,13	0.1849	0.0000	0.5377	Pin
13	Left shoulder	3,14	-0.1849	0.0000	0.2578	B&S
14	Left elbow	14,15	-0.1849	0.0000	0.5377	Pin

The joint mechanical properties define the relationship between the joint resistive torque and the joint angle and angular velocity. These properties include the joint spring and viscous torque characteristics. Frictional torque is currently not considered. Figure 18 shows the joint spring torque function. In this definition, a linear torque versus joint angle is prescribed until the joint reaches stop

angle θ_u or θ_l. For angles beyond the joint stop, a quadratic or cubic restoring torque is added. When the joint is unloading, the restoring torque is multiplied by a fact of k_3, which takes into account the hysteresis of the joint. This is in fact a "soft stop". A joint may also be subject to a "hard stop" (denoted as θ_l^h and θ_u^h for lower and upper stop respectively) where the joint cannot exceed the stop angle. Using constraint condition instead of restoring torques fulfills a hard stop. Due to the difficult in measuring joint viscosity, constant damping coefficient is assumed for most joints. The spring and damping parameters and joint stops used in the model are given in Table 7.

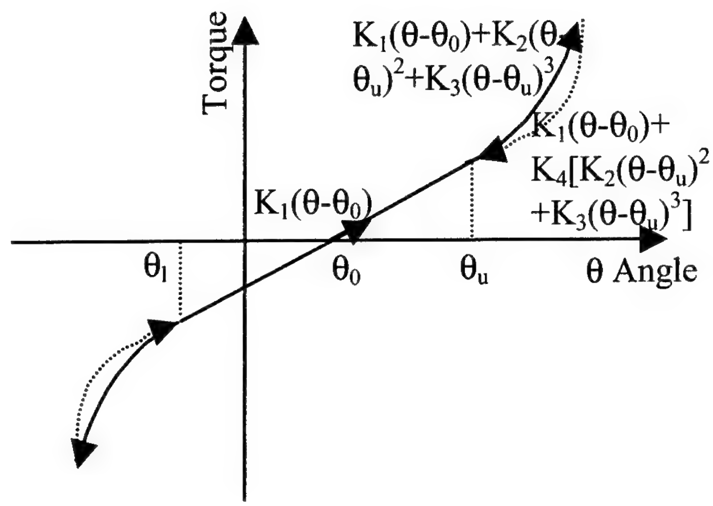

Figure 18 Joint spring torque

Table 7 Joint Mechanical Properties and Joint Stop

No.	Joint	DOF	K_1	K_2	K_3	K_4	θ_l	θ_u	θ_l^h	θ_u^h	η
1	P	Flx	0	1.13	0	1.0	-2.26	2.26	-5	30	0.011
		Rot	0	1.13	0	1.0	-0.565	0.565	-30	30	0.011
2	W	Flx	0	1.13	0	1.0	-2.26	2.26	-5	60	0.011
		Rot	0	1.13	0	1.0	-3.955	3.955	-30	30	0.011
3	NP	Flx	0	0.565	0	1.0	-2.825	2.825	-25	45	0.011
		Rot	0	1.13	0	1.0	-3.955	3.955	-30	30	0.011
4	HP	Flx	0	0.565	0	1.0	-2.825	2.825	-20	45	0.011
		Rot	0	1.13	0	1.0	-3.955	3.955	-30	30	0.011
5	RH	Flx	0	1.13	0	1.0	-7.909	7.909	0	90	0.011
		Rot	0	0.09	0	1.0	-4.52	4.52	-30	30	0.011
6	RK	Flx	0	0.203	0	1.0	-6.779	6.779	-90	0	0.011
7	RA	Flx	0	0.791	0	1.0	-3.955	3.955	0	0	0.011
8	LH	Flx	0	1.13	0	1.0	-7.909	7.909	0	90	0.011
		Rot	0	0.09	0	1.0	-4.52	4.52	-30	30	0.011
9	LK	Flx	0	0.203	0	1.0	-6.779	6.779	-90	0	0.011

No.	Joint	DOF	K_1	K_2	K_3	K_4	θ_l	θ_u	θ_l^h	θ_u^h	η
10	LA	Flx	0	0.791	0	1.0	-3.955	3.955	0	0	0.011
11	RS	Flx	0	1.13	0	1.0	-13.841	13.841	-60	60	0.011
		Rot	0	1.13	0	1.0	-7.344	7.344	-30	30	0.011
12	RE	Flx	0	0.203	0	1.0	-7.909	7.909	0	120	0.011
13	LS	Flx	0	1.13	0	1.0	-13.841	13.841	-60	60	0.011
		Rot	0	1.13	0	1.0	-7.344	7.344	-30	30	0.011
14	LE	Flx	0	0.203	0	1.0	-7.909	7.909	0	120	0.011

4.1.3 Simulation Results

From the airbag tests, the load when the airbag hit on the surrogate was estimated. Using this estimated load, the response of a standing person hit by the airbag was simulated. Figure 19 shows the animation of the person's response.

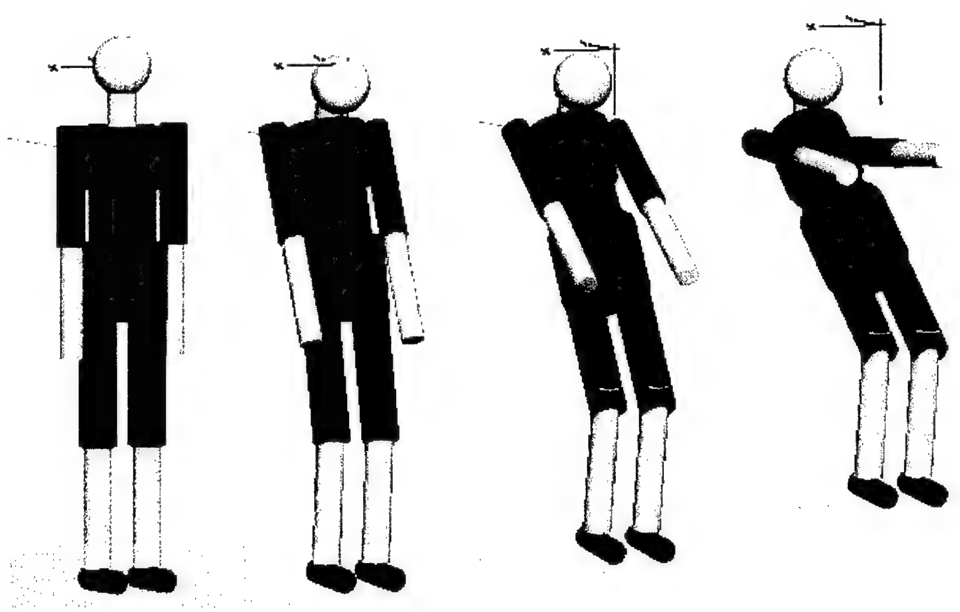

Figure 19 Animation of an airbag hit on a standing human model

Figure 20 gives the comparison of the chest accelerations of simulated from the human model and measured in the surrogate test. The human model shows higher acceleration than the surrogate. Figure 21 gives the accelerations of the different parts of the human model.

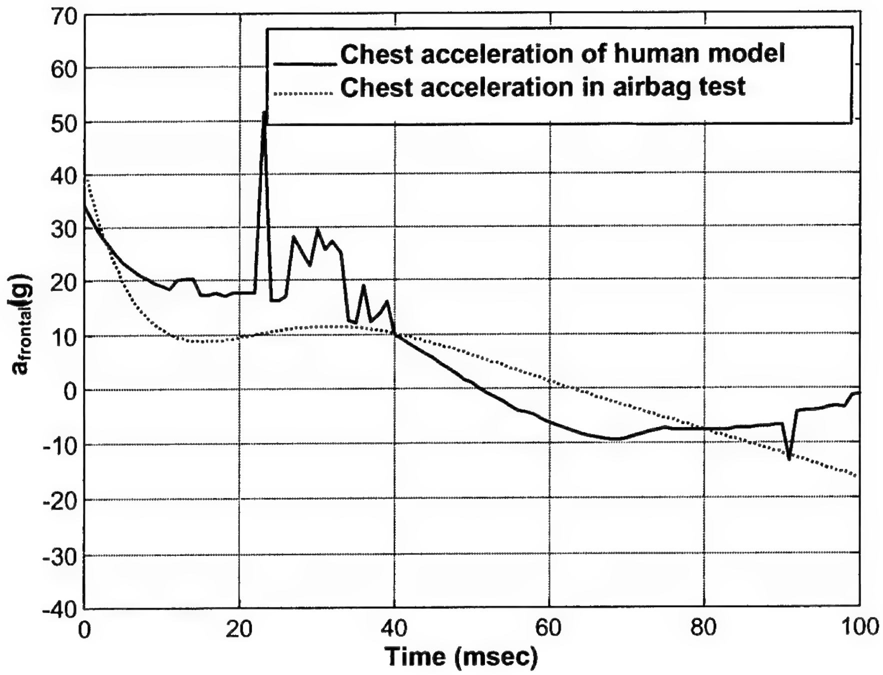

Figure 20 Comparison of the chest accelerations of the human model and the surrogate

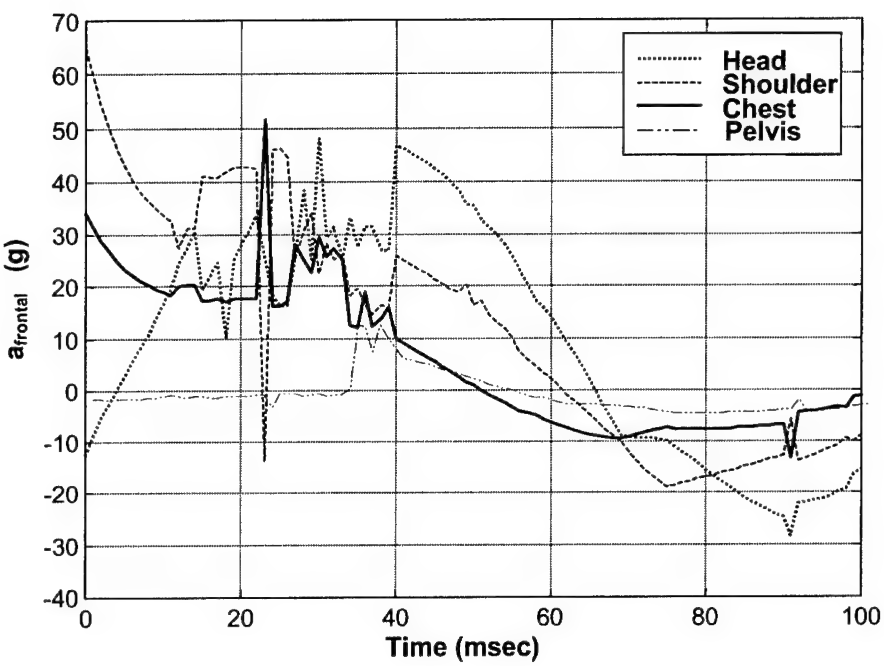

Figure 21 Accelerations of the different parts of the human model

Another situation was also simulated. It assumed that the human model was hit in the chest by a bullet. The bullet carried a moment of 10 Ns and the load lasted 1 millisecond. The accelerations of different parts of the human are given in Figure 22. The different parts responded to the bullet impact load almost synchronously since the loading was very short. However the magnitude of the response varies significantly from one part to another. This means the placement of the sensor will be important in distinguishing different events.

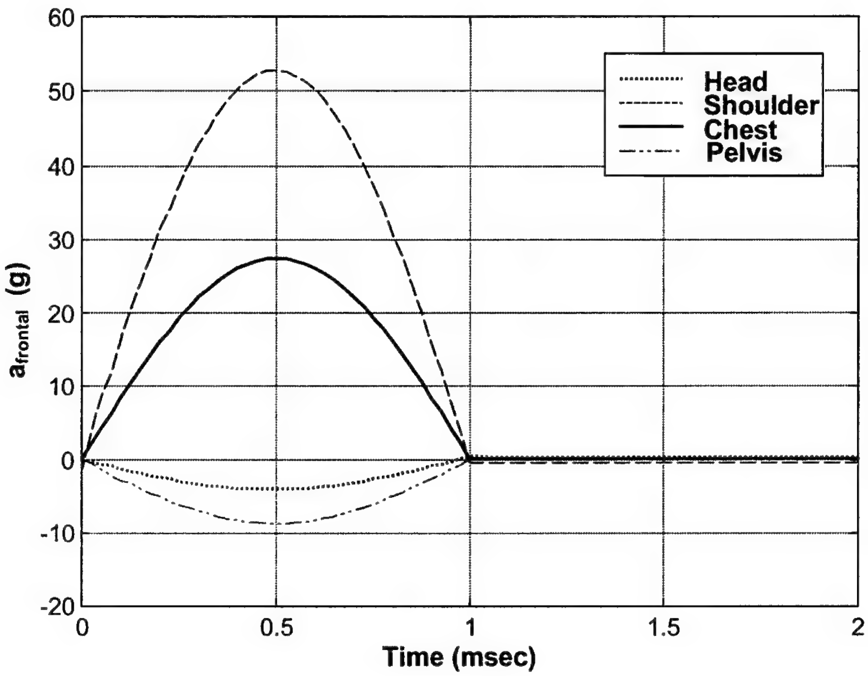

Figure 22 Acceleration of different parts of the human model when it is shot by a bullet

These simulation results suggest that biomechanical modeling combined with experiments can offer means to deal with problems which cannot be solved solely by experiments (it is impossible to hit a volunteer with an airbag or shoot him).

4.2 Modeling Human Locomotion

Human response during normal activities is significantly different from that in traumatic events. In traumatic events, a person has little time to react to the incoming action and it functions like a pure mechanical system. The response is primarily compulsive. On the other hand normal activities like locomotion are voluntary. Neural system directs and coordinates the activities of each muscle. The net forces and torques are generated at the articulations, which ultimately leads to such activities as walking, running or jumping (Winter, 1990).

The modeling of human locomotion is a very complicated topic. Different levels of models can be developed. Kinematic models provide information about the position, velocity and acceleration of human body. Kinetic models further deals with the forces and torques at each articulation. Muscle models can solve the forces and activities related to each muscle. The simulation of the whole locomotion process must involve all these models plus some control mechanisms.

Here only a simple kinematic model is developed since only the acceleration is the concern. The model is based on the work of Blickhan (1989) and McMahon and Cheng (1990). It predicts the acceleration of different body parts when a person hops in place continuously. The model results are compared with the data measured by the DRM.

4.2.1 Description of the model

It has been suggested that the analogy of hopping to a simple spring-mass system may be appropriate (Blickhan, 1989). This means human muscle skeletal system acts as an actively driven spring mass system (as shown in Figure 23).

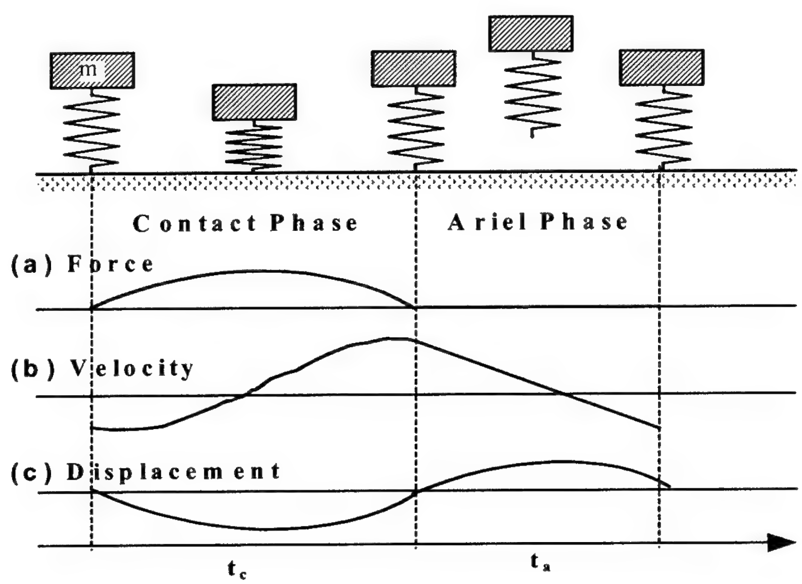

Figure 23 Spring-mass hopping model

One cycle of hopping in place can be separated into two phases. In the contact phase, the spring is in contact with the ground. Force develops in the spring. The displacement is negative, which means the body moves closer to the ground. In the beginning of the contact phase, the direction of velocity is toward the ground. By the end of the contact phase, when the body is about to leave the ground, the take-off velocity is positive. During the aerial phase, there is no deformation in the spring. The body moves as a free fall object with an initial velocity. The governing equations for the model are as follows:

$$\begin{cases} my''+ky = mg \ (t \le t_c) \\ my''+ky = 0 \quad (t_c \le t \le t_c + t_a) \end{cases}$$ Equation (1)

where m is the mass of the body, k the stiffness of the spring, y the displacement, g the gravity. t_c and t_a indicate the contact time and aerial time respectively. y" denotes the second derivative of displacement with respective to time (acceleration). This equation can easily be solved.

This model assumes all parts of the body moves in the same manner, which is obviously not true. Here it is assumed that the hip joint following the equation (1). All the other joints move with respect to the neighboring joints in the prescribed patterns.

The model is developed in the Matlab®, a general mathematical, numerical and graphics software. The schematic of the animation of one cycle of hop in place is given in Figure 24.

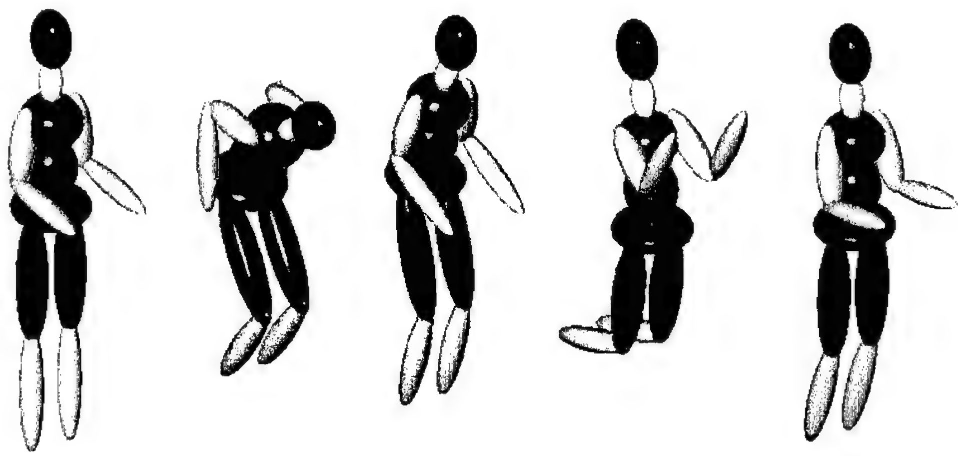

Figure 24 Animation of one cycle of hop in place

4.2.2 An example of model results

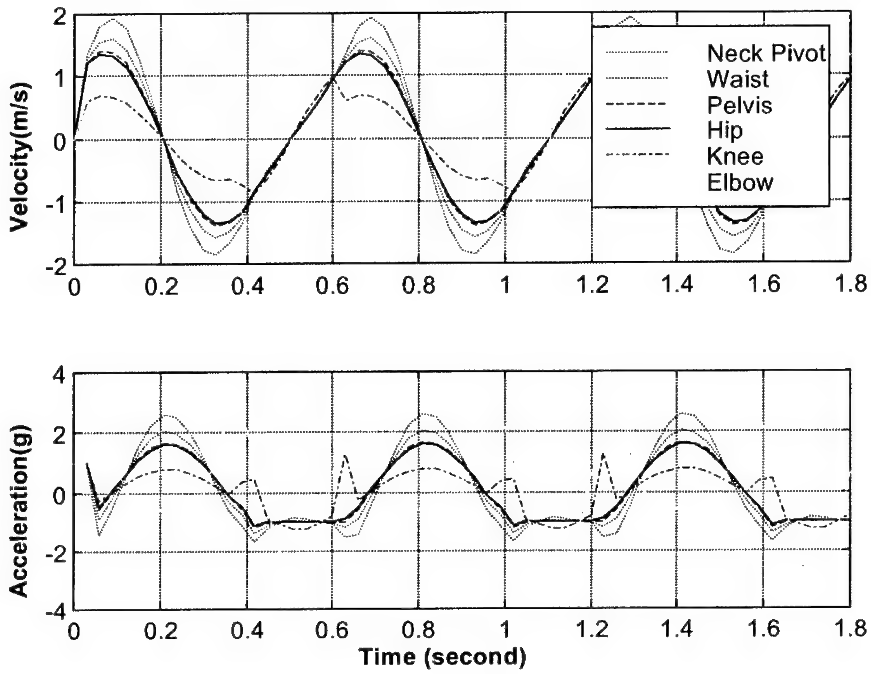

Figure 25 Velocity and acceleration of different joints with T_C=0.38, T_A=0.22

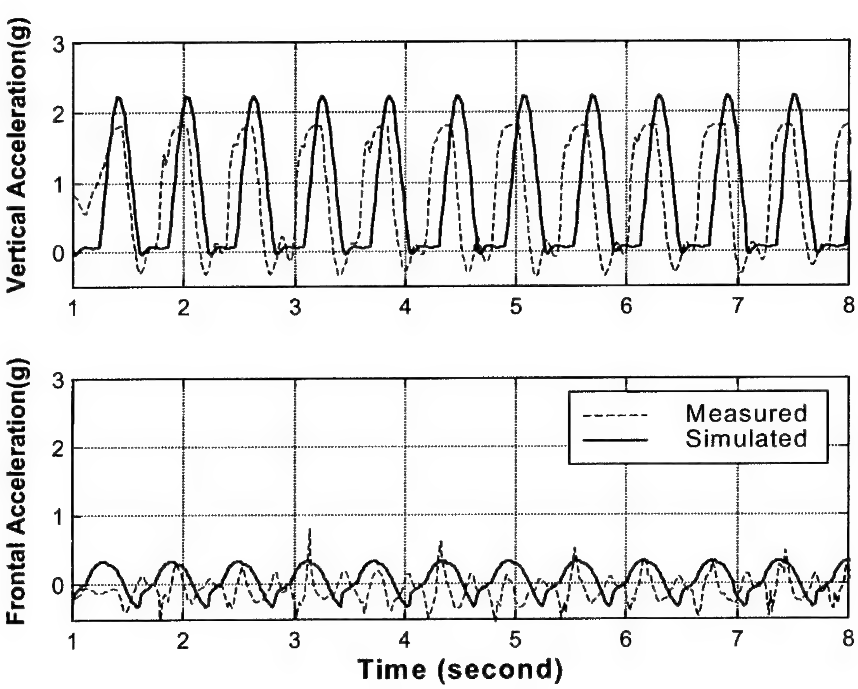

Figure 26 Comparison of measured and simulated hip acceleration in hopping

Figure 25 shows the vertical velocities and accelerations at the different joints of the body when the contact time is about 0.38 second and the aerial time about 0.22 second. These values are chosen to match the data measured by DRM.

Figure 26, which gives the comparison of measured and simulated hip accelerations, suggests this simple model matches favorably with experiment results. It also suggests that because its scale is limited to 2G, DRM might not capture the peak acceleration even in this simple locomotion. But the discrepancy is small.

4.3 Summary

Models were developed in this section to simulate the response of human under normal and traumatic situations. The model for traumatic events is an articulated rigid body model. When combined with experiment data, this model can provide detailed human response under various situations. It will facilitate the systematical development of the best injury detection system. However, due to the lack of human data, this model has not been verified. Future work will be needed to collect more data, to verify and refine the model.

The normal response model developed here is a simple kinematic model for hopping in place. It shows that even a simple model can match well with real situation. However, modeling human locomotion is a very complicated topic. Different models might be needed for different types of locomotion and different levels of models might be needed to serve different purposes. Further work in this area will be necessary to understand human locomotion and thus distinguish it from traumatic events.

5.0 Conclusions and Recommendations

This report describes two phases of work. The experiment phase used the DRM and its modified version DRM-G10 to collect normal, traumatic and physiological response data. The modeling phase developed models to simulate human response in the normal and traumatic events. The major findings are summarized as follows

1. The DRM measures most normal activities adequately.
2. During a traumatic event, the detected signal diminishes away with the location of the sensor. It was most distinctive when placed on the body. It became less significant when placed on the frame and was not distinguishable from normal motion when placed inside the backpack.
3. The accelerometer used in the DRM is sensitive enough and the signal is still significant on the other side of the body, maybe even in the frame.
4. For ballistic detection to be possible, however, the current system will have to be modified, which includes:
    - The full range of the accelerometers will have to be used and sampled at a high rate.
    - The sensor will have to be more tightly coupled to the body than provided by the backpack. The frame might be OK, body-mounted even better.
    - The detection scheme will have to take advantage of the short duration to distinguish a traumatic event. Amplitude will not be enough.
5. Mechanical modeling of traumatic and normal events is feasible, agrees at least qualitatively with test data, and will be necessary in the systematic development of the best detection system.

This initial investigation is encouraging and indicates that current accelerometer technology, reasonably coupled to the body, can detect a ballistic impact event on a surrogate target. Development of a system, integrated in Land Warrior and proven for ballistic impact to a soldier, requires that a number of issues be resolved.

1. The correlation between human response and manikin response to ballistic loading should be understood.
2. More data are needed from a wider range of traumatic events (bullet to the head) and normal events (riding in a car).
3. The sensor placement and mounting a critical to the observed response and must be selected both for the response and for the practicality of implementing in LW.
4. A robust discrimination algorithm must be developed and tested.

These issues can be resolved by a combination of laboratory testing of humans and surrogates and use of mathematical modeling to guide sensor requirements, placement, and interpretation.

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